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WADC TECHNICAL REPORT 52-121

DEVELOPMENT OF TEMPERATURE-SENSING ELEMENTS FOR JET ENGINES

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ARMOUR RESEARCH FOUNDATION

APRIL 1952

WRIGHT AIR DEVELOPMENT CENTER

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WADC TECHNICAL REPORT 52-121

DEVELOPMENT OF TEMPERATURE-SENSING ELEMENTS FOR JET ENGINES

Gary Steven
W. C. Troy

Armour Research Foundation

April 1952

Power Plant Laboratory
Contract No. AF33(038)-17637
RDO No. 540-20

Wright Air Development Center
Air Research & Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the Armour Research Foundation, Chicago, Illinois, under USAF Contract No. AF33(038)-17637. The contract was initiated under the research and development project identified by RDO No. 540-20, Temperature Sensing Elements; it was administered under the direction of the Power Plant Laboratory, Wright Air Development Center, with Mr. N. Erkeneff and Lt. D. M. Perkins acting as Project Engineers.

ABSTRACT

The thermoelectric characteristics were determined for the thermocouple $MoSi_2$/Pt and ZrB_2/Pt. Instability of emf output disqualifies these combinations from high temperature application in jet engine control.

Chromel-alumel thermocouples were fabricated with various shapes of the hot junction. The design was intended to achieve rapid heat transfer from the gas stream to the metal and adequate structural strength of the assembly. Characteristic response times were determined at Armour Research in a hot gas jet with a mass flow rate of 4 lb/sec/ft^2. The recorded data represent the intersection of the time sweep on an oscillograph screen with the 63.2% mark of the thermal emf rise.

The best response, namely 0.75 second, was obtained from a thermocouple with a butt welded hot junction of thin-wall tubular elements (0.065" OD x 0.005" wall). Vibration test data for this construction were not available for inclusion in this report.

The report summarizes investigations carried out over the period February 23, 1951 to February 23, 1952.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING OFFICER:

NORMAN C. APPOLD
Colonel, USAF
Chief, Power Plant Laboratory

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SECTION I

INTRODUCTION

The purpose of this investigation was the design, assembly, and testing of rapid response thermocouples for use in turbojet engine exhaust gases. It was desired to obtain from the temperature sensing element the following operating characteristics:

a. Temperature measurement with stable emf output up to 3000°F for a period of 150 hours.

b. A characteristic response time of not greater than 0.5 second when measured in a gas stream having a mass flow rate of 6 lbs/sq ft/sec.

c. A velocity recovery factor of not less than 0.9.

d. An accuracy of the sensing element of at least ± 1% below 2000°F, and not to exceed ± 20°F above 2000°F.

e. The thermocouple also shall be capable of withstanding 100 hours of vibration at 35 g within the frequency range of 10 to 1000 cps while maintained at maximum rated temperature.

f. The thermocouple shall be able to withstand 100 cycles of thermal shock from maximum rated temperature to -65°F in a gas stream of minimum velocity of 250 ft/sec.

At the present state of development of refractory materials, it was recognized that it would be extremely difficult to combine thermoelectric elements into a thermocouple embodying all the requirements of the specification. Rather, it was attempted to attack separately individual problems, such as high temperature oxidation resistance, thermoelectric stability, and a design for rapid response to temperature changes. It was hoped that any contribution made by this investigation would constitute a building block in the integrated design of the ideal thermocouple for jet engine control application.

For the purpose of experimental exploration, the project was, therefore, divided into two distinct phases:

1. Using the combination of Chromel-Alumel metal, thermocouples were fabricated with various geometric configurations of the hot junction. Essentially, an effort was made to induce rapid heat transfer from the gas stream to the thermocouple while maintaining a high degree of structural rigidity.

2. Conductive refractory materials were tested for suitability as elements of high temperature thermocouples.

A successful rapid response temperature sensing element would have to combine the best features of materials and construction. In the development stage of the program, however, advantage was taken of the ease of fabrication of commercial thermocouple materials in producing various configurations of the hot junction. The metalloid refractories were fabricated by powder metallurgical techniques, because the extreme hardness of the sintered bodies preclude conventional machining operations and would require diamond drilling and grinding for the shaping of thin-wall elements.

SECTION II

EXPERIMENTAL SETUP AND TESTING PROCEDURE

High Velocity Jet Tube; Thermocouple Response Determination

A laboratory setup was made to test the response time of different hot junction tip shapes. With the available equipment, it was not possible to develop the desired mass flow rate of 6 $lbs/ft^2/sec$. Hence, the test results obtained were useful only in comparing the effect of shape and dimension on the response rate that could be achieved with the thermocouple.

The test setup in Figure 1 shows the Selas gas mixer that was used in supplying the water-cooled burner with the proper ratio of gas to air. A maximum pumping capacity of 1400 cu ft/hr was available from this unit. The hot flame from the burner tip is passed through a second water-cooled jet tube containing the installation for producing sudden changes in the environmental conditions of the thermocouple. This rig resembles the installation at the National Bureau of Standards[1].

Initially, the thermocouple is immersed halfway into the jet tube, and is surrounded by an Inconel shielding tube at a right angle to the direction of the gas stream. This tube serves as a duct for a cold air column which maintains the thermocouple tip at ambient air temperature. When the air is shut off, the spring-actuated Inconel tube drops into the passage below and the thermocouple is exposed abruptly to the hot gas stream. Response time measurements start from that instantaneous exposure.

A modification of the jet tube was necessitated later in the program, because of the flame holding action that occurred with tubular hot junction thermocouples (see Section IV, Experimental Results). In cooperation with Messrs. Fiock and Dahl, a new setup was made in which the burner was placed in a vertical position with the flame passing through a right angle bend of a three inch diameter pipe assembly. In this case, no water cooling was used for the walls of the jet tube. A coarse mesh stainless steel screen was placed in the horizontal section of the pipe to act as an additional flame holding protection.

1. A. I Dahl and Ernest F. Fiock, Journal of Research 45, 292, 1950.

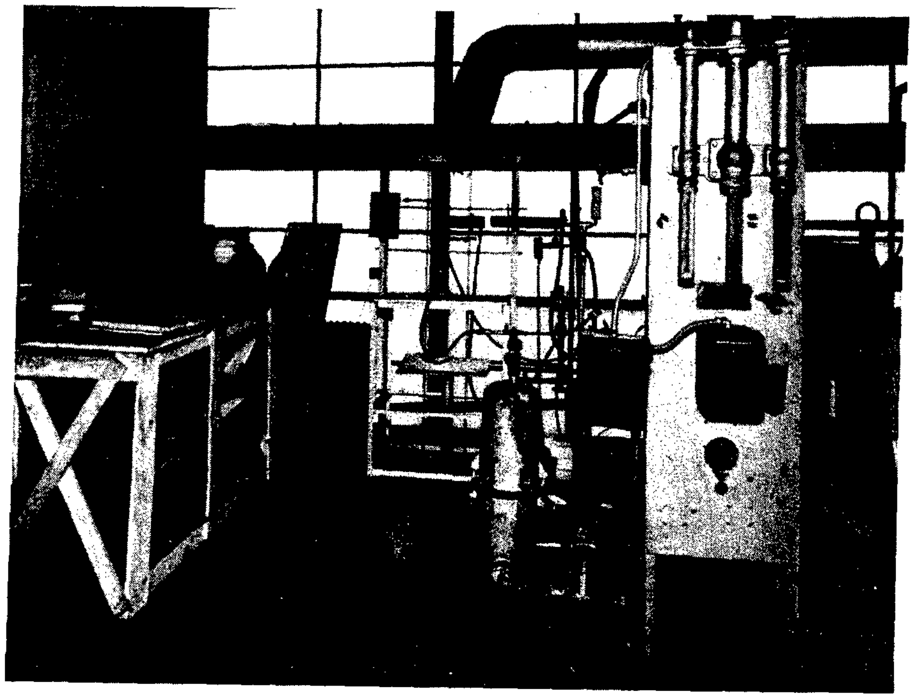


Figure 1

Photograph of the test setup used in comparing response times of thermocouples with various hot junction constructions.

The air-gas ratio from the Selas mixer is supplied to a water-cooled burner which injects the hot flame into the jet tube. Response of the thermocouple to rapid gas temperature changes is read directly on the screen of a DC oscilloscope.

Various methods were used in determining response times of thermocouples. For responses of several seconds magnitude, a millivoltmeter was timed at 63.2% of the maximum voltage reading. A direct inking oscillograph (Brush recorder) was used to trace emf time records of more responsive thermocouples. This method did not prove successful because of the radio noise interference from RF equipment located throughout the Metals Research Building.

The instrumentation that was perfected to yield reproducible results involved the use of a Dumont DC cathode ray oscillograph.

In testing the response time of a thermocouple assembly, the thermal emf output was first shunted into a millivoltmeter, while the gas flow was adjusted to produce a reading of about 40 millivolts (equivalent to 1800°F). The vertical displacement of the sweep on the oscilloscope screen then corresponded to the full emf output of the thermocouple at the selected mass flow rate of the gas stream.

An area that encloses 63.2% of this emf time field was masked off in a vertical direction, and time scale markings were provided on both the upper and lower boundary. The interval corresponding to the characteristic response time could be measured from the point of initial rise of the sweep to the point of intersection with the upper masking boundary. A typical trace of a sweep is shown in the photograph of the oscillograph screen in Figure 2. It was found that the sweep travels with a nonlinear horizontal velocity, and this accounts for the uneven markings on the time scale. A calibration was easily achieved by means of a standing wave from a 60 cycle 110 v line input. In order to avoid taking time readings in the crowded right hand area of the field, the time scale could be spread out at will to comprise two and even three traverses for a complete response time cycle.

All data included in this report were obtained by the method described above and represent the mean of at least five determinations. The maximum deviation from the mean value is ± 0.1 second.

Furnace Setup Used In the Calibration of High Temperature Thermocouples

A molybdenum-wound, molybdenum-shielded resistance furnace is shown in Figure 3. This furnace can be operated beneath a water-cooled bell jar, and it is capable of producing muffle temperatures of 3600°F.

The thermal emf-temperature relation was obtained for several combinations of refractory metalloids vs platinum metal. The reference couple was an unprotected Pt/Pt - 10% Rh thermocouple in juxtaposition with the test thermocouple.

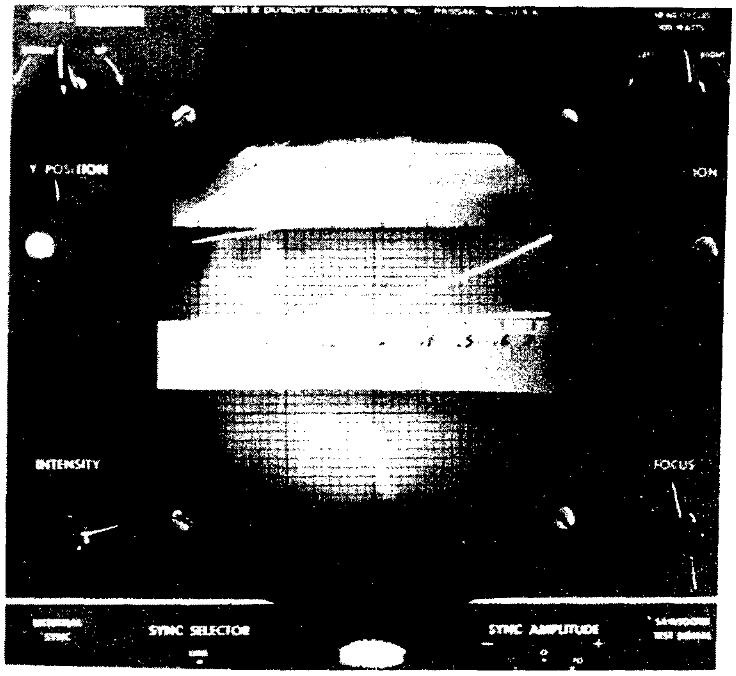


Figure 2

Representative oscillograph recording of the emf response curve for thermocouples tested in the setup shown in Figure 1.

The upper mask encases a field representing 63.2% of the maximum thermal emf output.

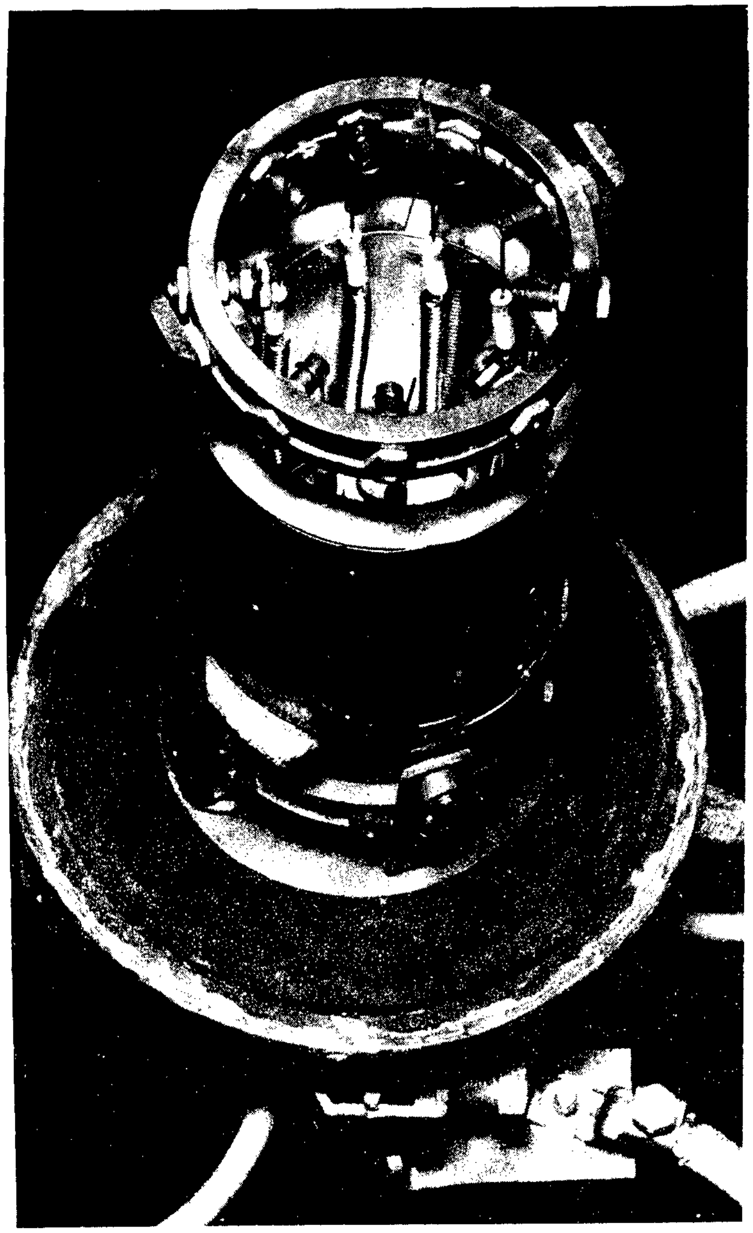


Figure 3

Top view of the molybdenum-wound resistance element furnace used in the calibration of refractory thermocouples. The triple radiation shield cover and the 1" alumina crucible are not shown in the photograph.

SECTION III

FABRICATION OF RAPID RESPONSE THERMOCOUPLES

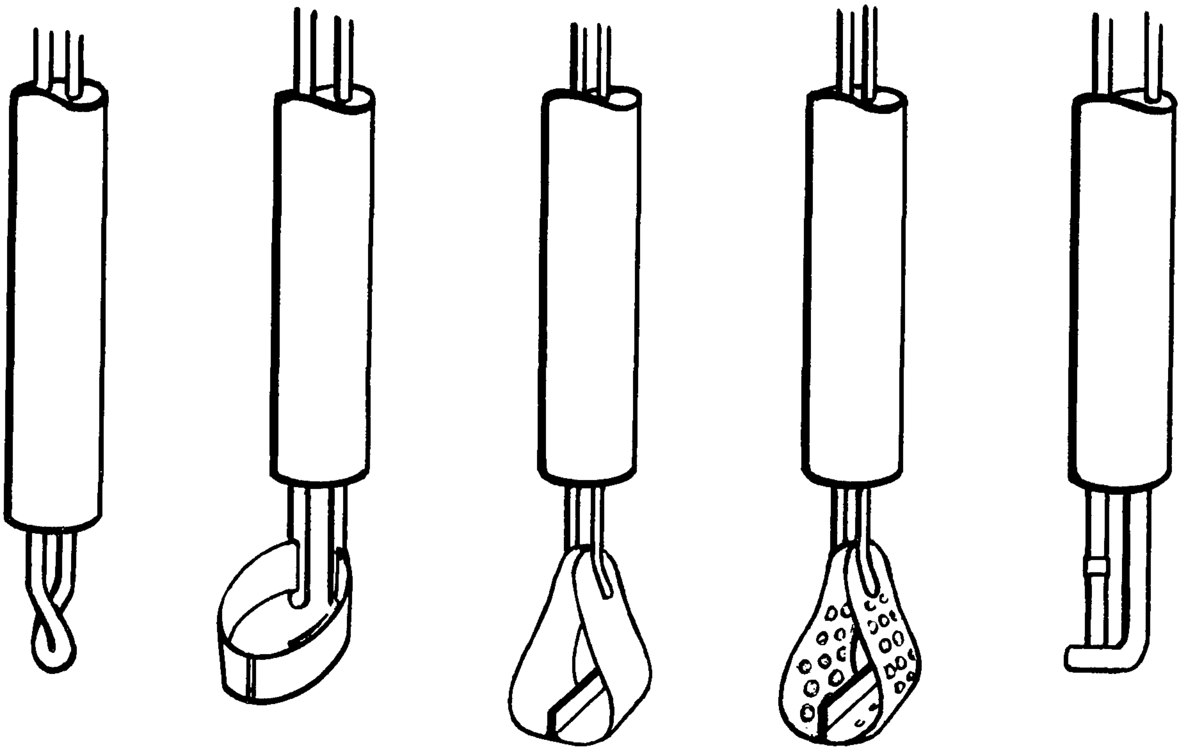
The object in designing different shapes for the thermocouple hot junction was to produce a high coefficient of heat transfer from the hot gas to the metal, combined with adequate structural strength. A high surface to mass ratio is necessary to achieve rapid response to temperature changes. Figure 4 contains sketches of various basic thermocouple designs, embodying different thermodynamic considerations. The construction shown in Figure 4(b) achieves stagnation of the gas stream at the leading edge of a hollow streamlined section. The design shown in Figure 4(c) offers little resistance to the gas flow and achieves contact of hot gases with a large surface area of the thermocouple hot junction. The design pictured by Figure 4(d) was developed in order to incorporate in the circuit of the thermocouple a radiation shield surrounding the hot junction seam weld. In piercing the wall of the tubular section periodically, a surface roughness pattern was created; it was intended as a further expansion of the available surface area and was thought to create turbulence inside the hot junction enclosure.

The design of the thermocouple shown in Figure 4(e) consists of thin-wall tubular elements, butt welded to form the hot junction; in this case, structural rigidity against the distributed load of the gas pressure is coupled with a favorable distribution of a small metal mass away from the neutral axis.

The photographs in Figure 5 and Figure 6 show the successive steps in the fabrication of thermocouples 4(d) and 4(e), respectively. In the first construction, the thermoelement strips were cold rolled from 11 gage thermocouple wire. They were then perforated with a pointed, tetragonal tool and torch lap welded to form the hot junction. Excess metal was ground off to form a single gage thickness of the original metal strip. The radiation shield-type thermocouple was formed and weld attachments were made to heavy wires embedded in ceramic insulators.

In the case of the thin-wall tubular thermocouple hot junction (Figure 6), strips of Chromel and Alumel were lap welded and rolled out to the desired thickness. Open seam tubes were formed around music wire and again a welded attachment was made to No. 8 gage thermocouple wire.

Another method was attempted experimentally for increasing the rate of radiant heat energy transfer to the thermocouple hot junction. In this case, a conventional welded hot junction bead was surrounded by a loosely-woven maze of 0.004 inch stainless steel wire.



Dimension of Thermocouple Hot Junction	Characteristic Response Time in Seconds 63.2% of Maximum Thermal Emf Output				
	(a)	(b)	(c)	(d)	(e)
0.040" round	1.60				
0.025" round	1.00				
w - 0.138" t - 0.018"					
w - 0.150" t - 0.014"					
w - 0.147" t - 0.012"				2.15	
w - 0.145" t - 0.011"				2.05	
w - 0.138" t - 0.015"					
w - 0.377" t - 0.016"		1.65			
w - 0.375" t - 0.016"			2.10		
0.185" t - 0.10"				2.10	
0.325" t - 0.010"				2.30	
0.065" OD x 0.005"					0.75

w = width of thermocouple shield
t = thickness of thermocouple shield

Figure 4

Various thermocouple designs and their characteristic response time when tested at 4 lbs/sec ft^2 in test rig described in Figure 1.

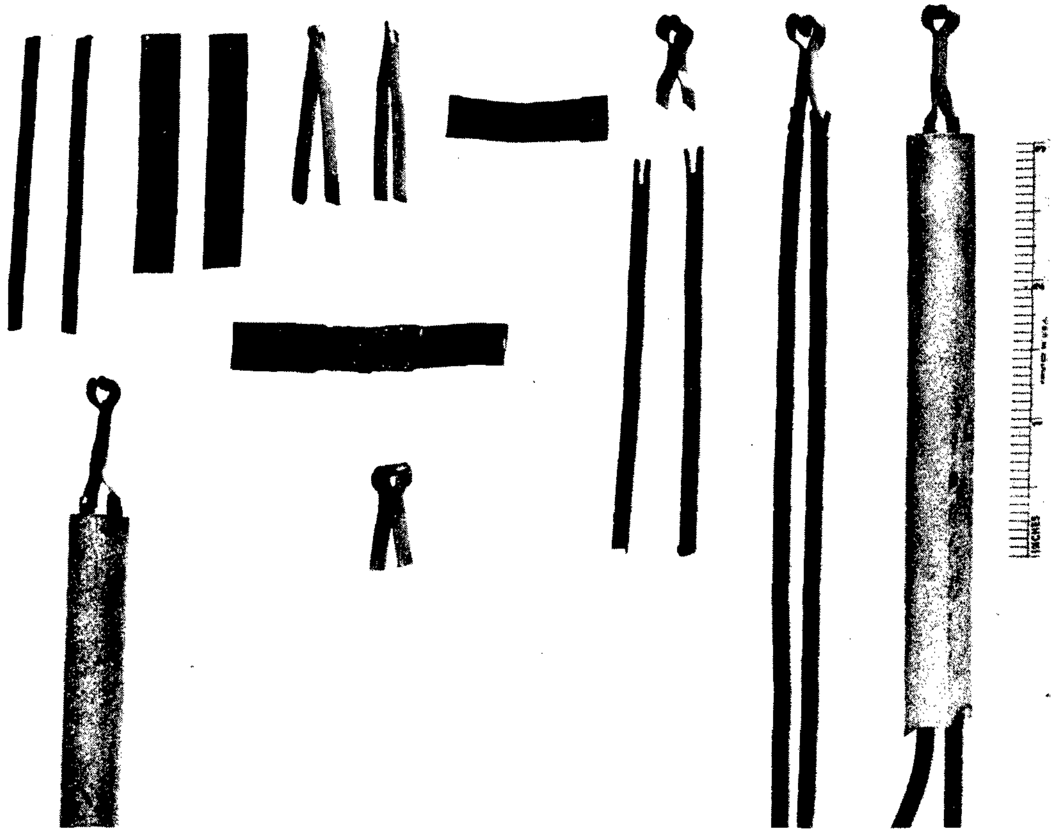


Figure 5

Photograph of elements going into the construction of the radiation shield-type hot junction.

This photograph also illustrates the steps in fabricating the perforated element from wire stock.

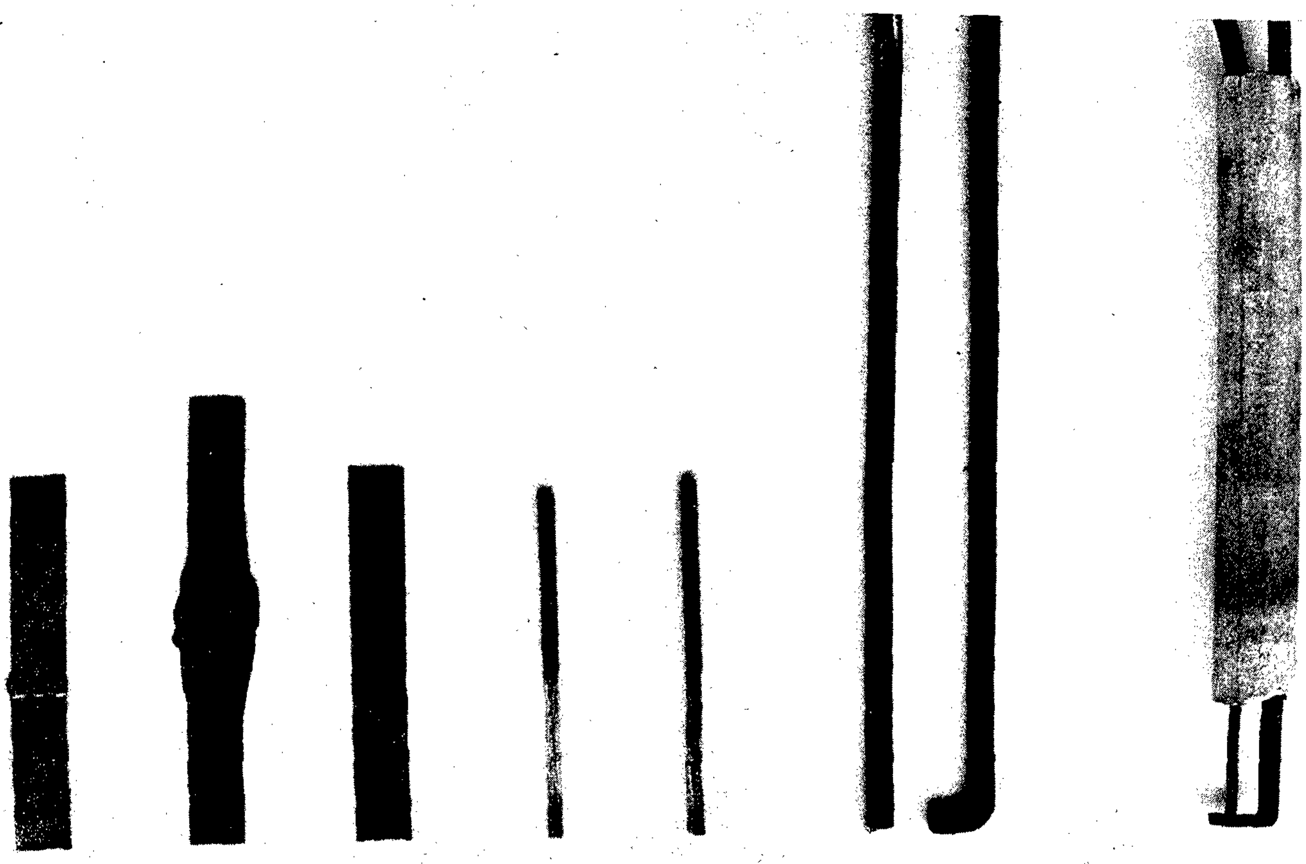


Figure 6

Successive steps used in the fabrication of a thin-wall tubular element thermocouple. The 0.005" wall, open seam tube is welded on either end to No. 8 gage structural reinforcing wires.

SECTION IV

EXPERIMENTAL RESULTS

Calibration of High Temperature Thermocouples

A siliconized molybdenum tube welded to an enclosed platinum wire was considered to be a favorable metal combination for use as high temperature thermocouples in oxidizing environment. This combination was suggested in the Proposal No. 50-192 for this investigation and formed the basis for the Purchase Requisition from Air Materiel Command.

It developed that this thermocouple had been tested by Minneapolis-Honeywell Regulator Company*.

The low peak thermal emf output of 1.8 v at 700°C, as well as the thermoelectric inversion, eliminated this thermocouple from consideration as a control device in jet engine application.

A thermocouple was formed from an extruded molybdenum disilicide tube about 1/8" OD x 1/32" wall,** three inches long and a ceramic insulated platinum wire was inserted into this tube. The assembly was welded shut at one end in a carbon arc. A cold junction was formed by inserting the open end of the $MoSi_2$ tube into a water-cooled copper jacket and attaching lead wires inside this holder. There could not be obtained reproducible emf output in several determinations of the thermoelectric characteristic of the thermocouple. An element of instability was introduced by the welding attachment between the platinum metal and the refractory intermetallic compound. A chemical reaction between the two materials has been observed at temperatures above 2000°F.

Although the thermal emf output was in the order of 16 millivolts to 25 millivolts in the temperature range from 2200°F to 3000°F, the inherent instability of this thermocouple combination makes it of doubtful value for jet engine control application.

Two pressed and sintered rods of zirconium diboride 1/4" diameter x 3" long were supplied by the American Electro Metal Corporation. A thermocouple was formed by arc welding a 24-gage platinum wire to one end of the ZrB_2 bar. Table I shows the calibration of this thermocouple combination, which was

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* This information was transmitted in a letter dated 30 April 1951 from Headquarters, Air Development Center, Wright-Patterson Air Force Base, DCNEG3/RTD/jts.

** This pure $MoSi_2$ body was supplied by the Materials Section at NACA.

TABLE I

CALIBRATION OF THE ZrB_2/Pt THERMOCOUPLE

At the inversion point of the thermoelectric polarity, the emf output of the thermocouple became erratic. The recorded emf values were averaged from several constant temperature readings.

Thermal Emf Output of the ZrB_2/Pt thermocouple	Calibration Temp. Pt/Pt - 10% Rh thermocouple in juxtaposition with the hot junction of the ZrB_2/Pt thermocouple.	Cold Junction Temp. as measured with a Chromel-Alumel thermo-couple
millivolts	°F	°F
0.30	380	200
0.73	610	244
1.35	900	365
2.00	1240	470
2.33	1497	511
3.73	1916	581
-0.05	2071	568
-8.50	2313	665
-4.75	2464	710

Instability of emf output; erratic millivolt readings obtained by comparing its thermal emf output with that of a Pt/Pt - 10% Rh thermocouple. The heating chamber was a molybdenum-shielded, molybdenum-resistance furnace operating inside a water-cooled bell jar. Hydrogen gas was used as protective atmosphere during the run.

The short length of the ZrB_2 element caused appreciable heating of the "cold junction" end through thermal conduction along the rod and by radiation from the furnace muffle opening. Therefore, an auxiliary Chromel-Alumel thermocouple was used at this point to indicate the surrounding temperature.

At the higher temperatures, an inversion of the thermoelectric polarity was observed. Emf readings also tended to become erratic at constant furnace temperature settings. This inversion was obtained in three consecutive runs using different hot junction welds. It was concluded that the ZrB_2 is unsuitable as a thermocouple element for use in high-temperature sensing elements.

Characteristic Response Time for Various Hot Junction Constructions

The development program of hot junction design that resulted in the configuration shown in Figure 4(d) was based on response time evaluations carried out at Armour Research Foundation with the test rig pictured in Figure 1. Tests conducted with strips 0.020", 0.015" and 0.010" thickness, showed promising results for the thinner gages at our estimated mass flow rate of 4 $lbs/ft^2/sec$.

For every gage thickness, there could be determined an optimum length of the shielding tube which would result in minimum response time of the thermocouple. A determination of characteristic response time of this thermocouple design was made by Mr. Andrew I. Dahl, of the National Bureau of Standards, Gas Temperature Measurements, Combustion Section. The values reported were consistently higher than the response time reading obtained in the Armour test setup. A careful comparison of the test method showed that the tubular shape of the hot junction when exposed to the luminous gas flame would act as a flame holder for the burner jet. A redesign of the jet tube shown in Figure 1 to include a right angle bend and a flame holding screen brought about an agreement of the experimental data obtained at the two installations. A response time of 1.7 to 1.85 seconds was recorded. This thermocouple construction, therefore, was not found to be of interest as a high response temperature sensing element.

Three terminal-type thermocouple heads (BG Corporation, Model No. B-8800X1- were fitted with this shielding probe-type hot junction. Vibration tests are being conducted at Wright Field on these assemblies. The results of these tests were not available for inclusion in this report.

TABLE II

NATIONAL BUREAU OF STANDARDS RESPONSE TESTS OF TWO TUBULAR CHROMEL-ALUMEL THERMOCOUPLES 0.065" OD x 0.005" WALL

Position 1, the temperature sensing element is directly upstream from the support; position 2 measurements were taken with the sensing element in a plane at right angles to the axis of the pipe; position 3 is in a down-stream direction.

Characteristic Time - Seconds, at Flow Rates in $lb/sec\ ft^2$

	(Position No. 1)			(Position No. 2)			(Position No. 3)		
	2	4	6	2	4	6	2	4	6
				Unit No. 1					
	1.00	0.70	0.58	1.05	0.75	0.65	1.15	0.90	0.80
	1.00	0.72	0.60	1.10	0.70	0.70	1.15	0.95	0.80
	1.15	0.80	0.60	1.05	0.77	0.70	1.10	0.90	0.80
			0.65		0.75	0.65			
Mean	1.05	0.74 0.75*	0.61	1.07	0.74	0.67	1.13	0.92	0.80
				Unit No. 2					
	0.98	0.75	0.62	0.94	0.70	0.57	1.14	0.84	0.70
	1.08	0.70	0.58	0.94	0.71	0.63	1.18	0.94	0.70
	0.92	0.88	0.62	1.01	0.70	0.64	1.20	0.82	0.70
Mean	1.00	0.78 0.75*	0.61	0.96	0.70	0.61	1.17	0.87	0.70

* Mean value obtained at Armour Research Foundation.

Thermocouples made up of butt welded, thin-wall tubing (Figure 4(e)) were tested at Armour Research and at the National Bureau of Standards. The results of these tests are compiled in Table II.

A comparison was made between the response times of conventional (22 ga) bare wire thermocouples and the same thermocouples surrounded by a maze of 0.004" stainless steel wire. The effect of this envelope was to increase the characteristic time from 0.95 second to 1.95 seconds. It was observed that the upstream portion of the wire mesh attained the temperature of the gas stream very rapidly. The downstream section of the wire mesh sphere, on the other hand, required several seconds to reach temperature equilibrium with the gas stream. It appears, therefore, that a radiant wire mesh surrounding the hot junction of the thermocouple does not produce the anticipated reduction in response time.

SECTION V

DISCUSSION OF RESULTS

The phase of the project dealing with the selection of elements for use in high temperature thermocouples failed to uncover a combination that would be acceptable in the jet engine control application. Siliconized molybdenum vs iridium showed a low peak emf and an inversion of thermoelectric polarity. The $MoSi_2$/Pt and ZrB_2/Pt thermocouples yielded unstable emf readings. This preliminary survey indicates that a sizeable research program would be required to develop a new thermocouple between noble metals and the refractory metalloids.

In the construction of rapid response thermocouples, various shapes of hot junctions were tested at mass flow rates of 2 to 6 $lbs/ft^2/sec$. The response times obtained from butt welded tubular junctions approached most nearly the requirement of the specification, (0.61 second at 6 $lbs/sec\ ft^2$). Although vibration tests have not yet been conducted on this thermocouple construction, it is anticipated that the weld will resist failure from repetitive high cycle stresses.

The potential usefulness of a hollow thin-wall section in the hot junction region advises in favor of continued research effort in the direction of determining the ideal size and configuration of the thermocouple. In the present test samples there exists a longitudinal open seam in both elements of the thermocouple, thus reducing the flectural rigidity of the section. It is believed that seamless tubing could be flash welded and cold drawn to produce a junction of controlled cross-sectional dimensions. An alternative method would be the welding of solid rod lengths and subsequent drilling and grinding to size.